

Life Cycle Assessment of Solid State Lighting Applications

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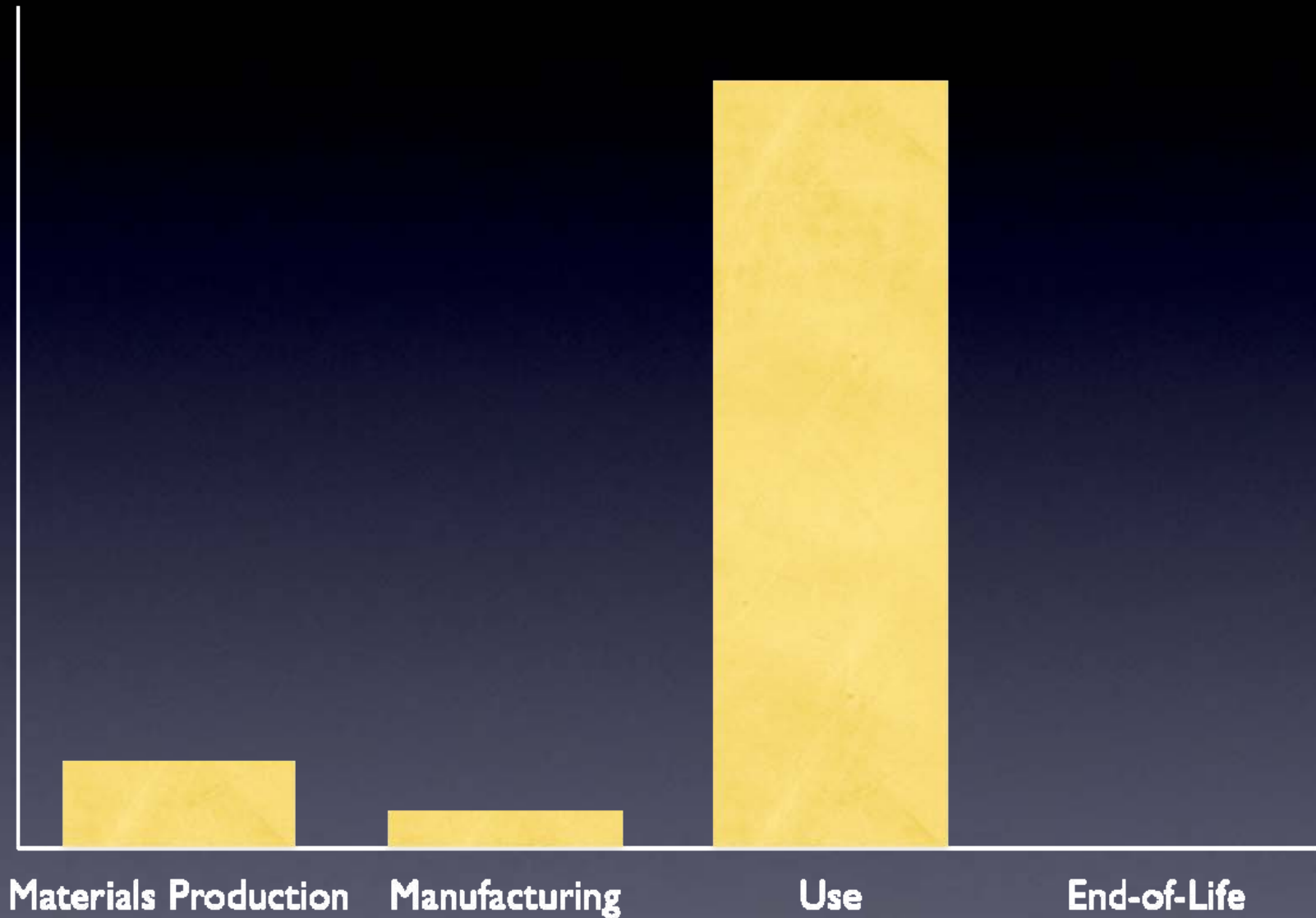
Project Goals

- Short term: Compare energy use of current SSL technology to existing mature technologies over the life cycle
- Long term: Identify existence of “materials of interest” over the SSL life cycle

Scope and Applicability

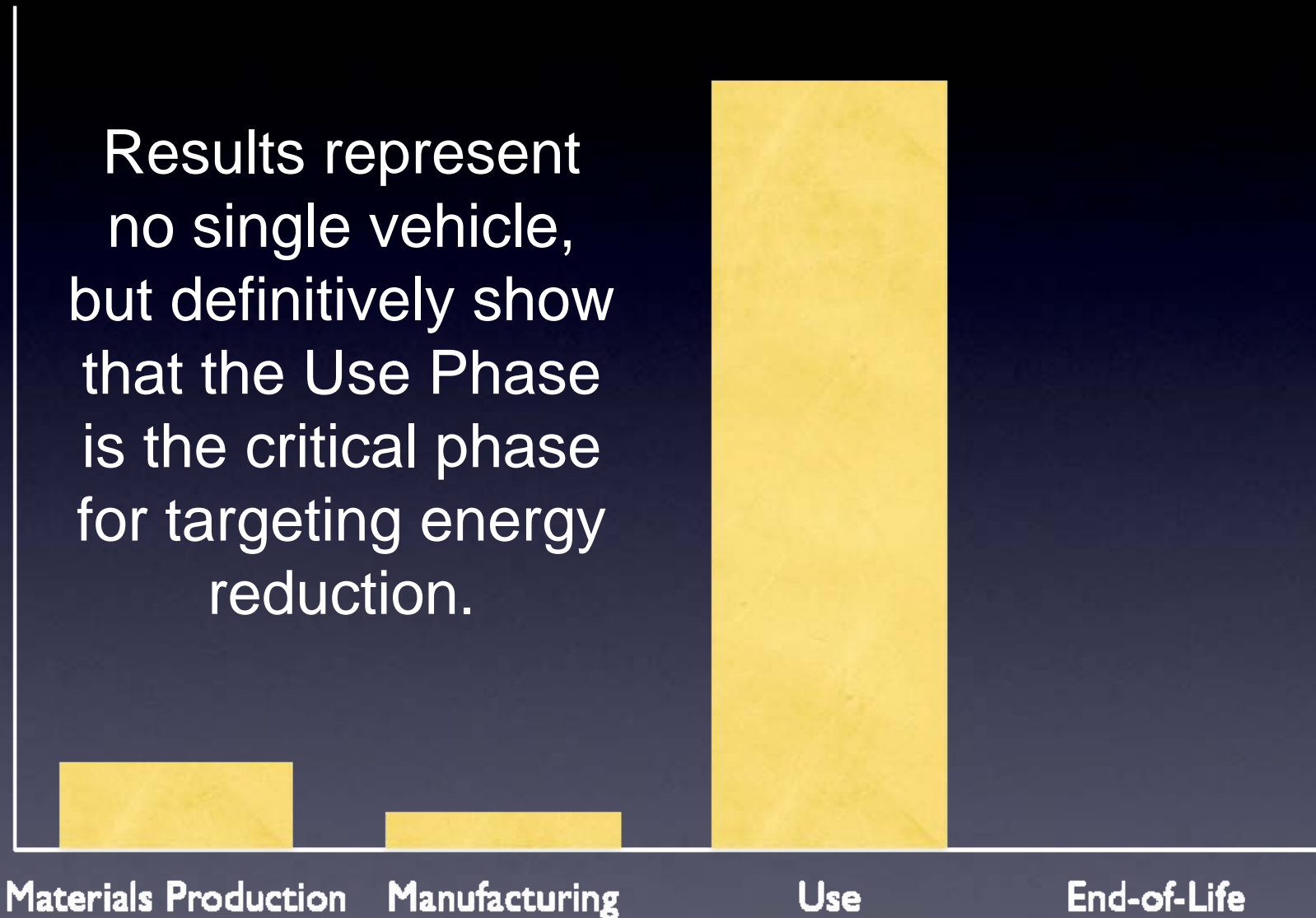
- Scope is to model the life cycle energy of a “generic” SSL product.
- We can't possibly do specific types and potential applications of SSL products.

Life Cycle Energy Inventory of a Generic U.S. Family Sedan



Sullivan, J. L., et al. "Life Cycle Inventory of a Generic U.S. Family Sedan" Society of Automotive Engineers, 1998.

Life Cycle Energy Inventory of a Generic U.S. Family Sedan



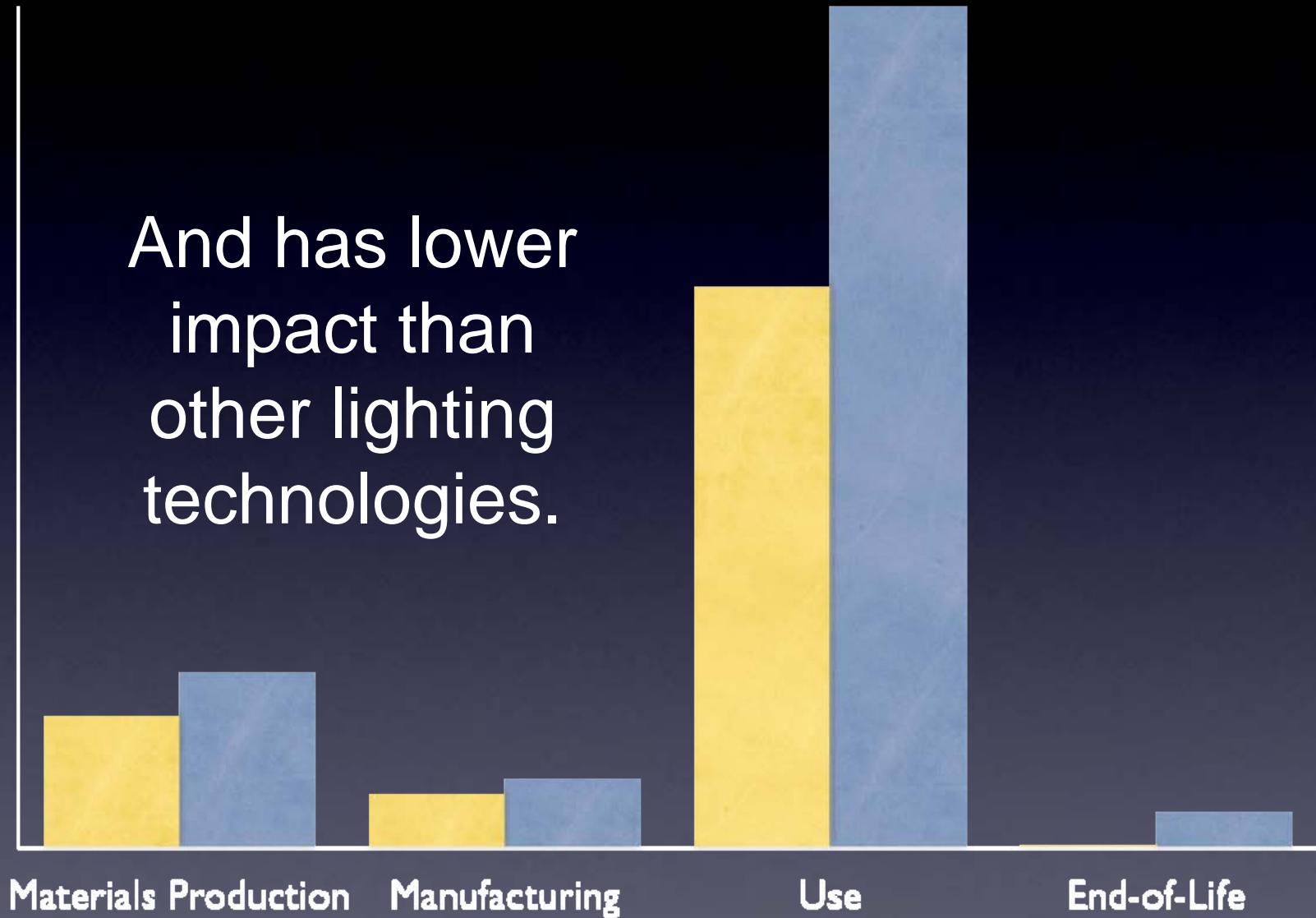
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■ SSL Product

■ CFL Product

And has lower
impact than
other lighting
technologies.



The question is, does the available
data support this goal?

Project Scope

Raw
Materials
Extraction

Materials and
Parts
Manufacturing

Product
Manufacturing

Use

End-
of-Life

Work To Date

Raw
Materials
Extraction

Materials and
Parts
Manufacturing

Product
Manufacturing

Use

End-
of-Life

Materials and
Parts
Manufacturing

Product
Manufacturing

Use

high purity process gases

metal organics

sapphire wafers

phosphors

bulk materials

device driver

other

Facilities, equipment,
waste processing



LED chip



LED array



Luminaire

Facilities, equipment,
waste processing



SSL replacement bulb,
downlight application

Materials and
Parts
Manufacturing

Product
Manufacturing

Use

high purity process gases

metal organics

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device driver

other

Facilities, equipment,
waste processing



LED chip



LED array



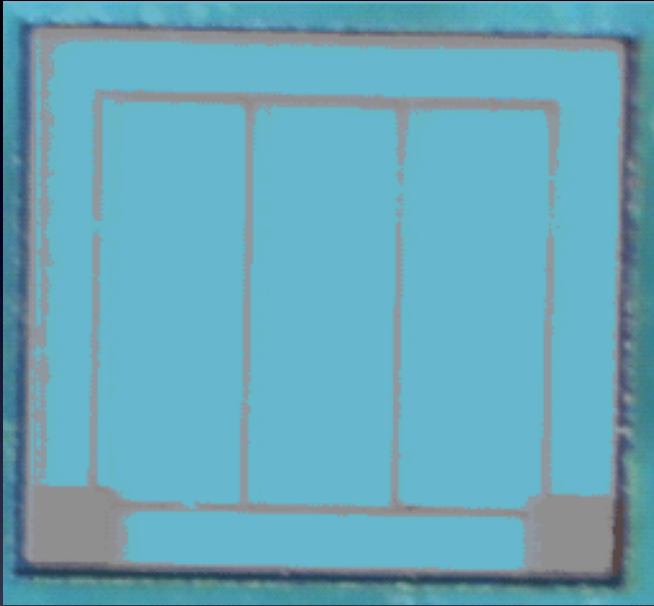
Luminaire

Facilities, equipment,
waste processing

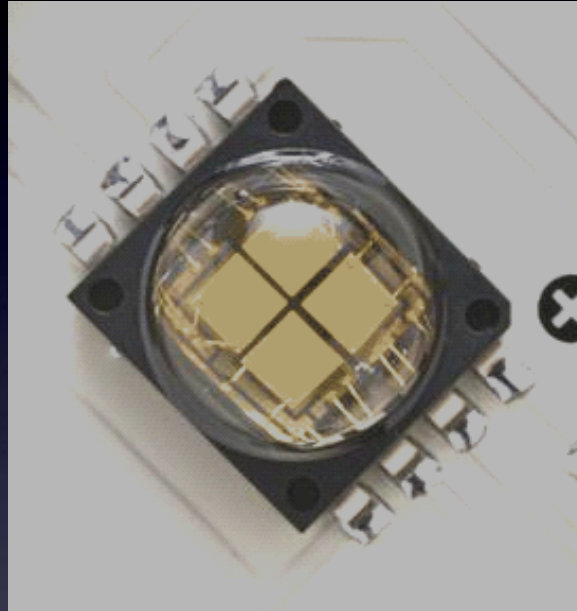


SSL replacement bulb,
downlight application

SSL Product Components



Chip



Device



Luminaire

Source: SSL Multi-year Program Plan

Our focus has currently been ONLY on the chip materials and production steps.

Assumptions for SSL Product

- Current generation replacement bulb, downlight application (CALIPER benchmark)
- Luminaire with an array of 20 HBLEDs
- Luminaire efficacy of 60 lm/w
- Luminaire lifetime of 25,000 hours

Materials Manufacturing Phase

- Reminder - LED materials only
- Includes: trimethylgallium, ammonia, sapphire wafers, silicon, yttrium, contact metals
- High purity levels would require significant energy input
- Initial estimates from bulk and industry grade LCIs, EIO-LCA method, logic chip LCIs

Materials Manufacturing

First Estimate

- Based on data from logic chip manufacturing (Krishnan, et al, ES&T, 2008), scaling by wafer size (LED wafer ~25% of logic chip wafer)
 - 300 - 600 kWh per wafer
 - 6 - 12 kWh per SSL product
- Need additional information on sapphire production

Product Manufacturing Phase

- Reminder - LED chip production only
- LED wafer processing a recipe of several steps
- Our approach is to estimate an energy value for each step, then add together corresponding values for the recipe
- GaN growth on sapphire substrate likely largest contributor to this LC phase (50% - 90%?)

CVD Estimates - 1

- Based on data from logic chip manufacturing (Krishnan, et al ES&T, 2008), scaling by wafer size (LED wafer ~25% of logic chip wafer)
 - Low pressure CVD - 22 kWh/wafer
 - High Density Plasma CVD - 37 kWh/wafer
- Average: 30 kWh/wafer, 0.6 kWh/SSL product

CVD Estimates - 2

- Equipment operating data
- Production scale set-up (six 2" wafers)
 - 44 kWh/wafer, 0.88 kWh/SSL product
- Lab scale set-up (one 3" wafer)
 - 39 kwh/wafer, 0.79 kWh/SSL product

Full LED Chip PM

- Including CVD, metal deposition, photolithography, etching, cleaning steps
 - 75 - 85 kWh/wafer
 - ~1.5 kWh/SSL product
- Including mounting, testing, packaging, phosphor coating, encapsulation
 - current “best guess” is double this

Facilities and equipment

- Based on data from logic chip manufacturing (Krishnan, et al ES&T, 2008) - how to scale?
- Equipment for fab plant
 - 200 - 700 kWh/wafer
 - 4 - 15 kWh/SSL product

Facilities and equipment

- Facilities - 40% of fab electricity consumption
 - ~350 kWh/wafer
 - 8 kWh/SSL product
- Most importantly, not negligible

Materials + Production

| | kWh/wafer | kWh/SSL |
|--------------------------|-------------|---------|
| Materials | 300 - 600 | 6 - 12 |
| LED Chip | 75 - 150 | 1.5 - 5 |
| Facilities and equipment | 550 - 1,050 | 12 - 23 |
| Total | 900 - 2,000 | 15 - 50 |

Product Manufacturing - CFL Lamp

- Gydesen and Maimann 1991 Study: Production of a 15 W CFL that provides 7.2 million lumen hours requires 1.4 kWh
- Tesco estimates that the production of a 15 W CFL that operates 4,000 hours requires 2.3 kWh
- Sima-Pro estimates for a 11 W CFL that operates 6,000 to 8,000 hours, and produces 600 lumens, requires 2.2 kWh

Product Manufacturing - Incandescent Lamp

- Gydesen and Maimann 1991 Study:
Production of a 60 W incandescent lamp that provides 0.73 million lumen hours requires 0.15 kWh
- Tesco estimates that the production of a 60 W incandescent lamp that operates 1,000 hours requires 0.9 kWh
- Sima-Pro estimates for a 60 W incandescent lamp that operates 1,000 hours, and produces 600 lumens, requires 0.2 kWh

Use Phase

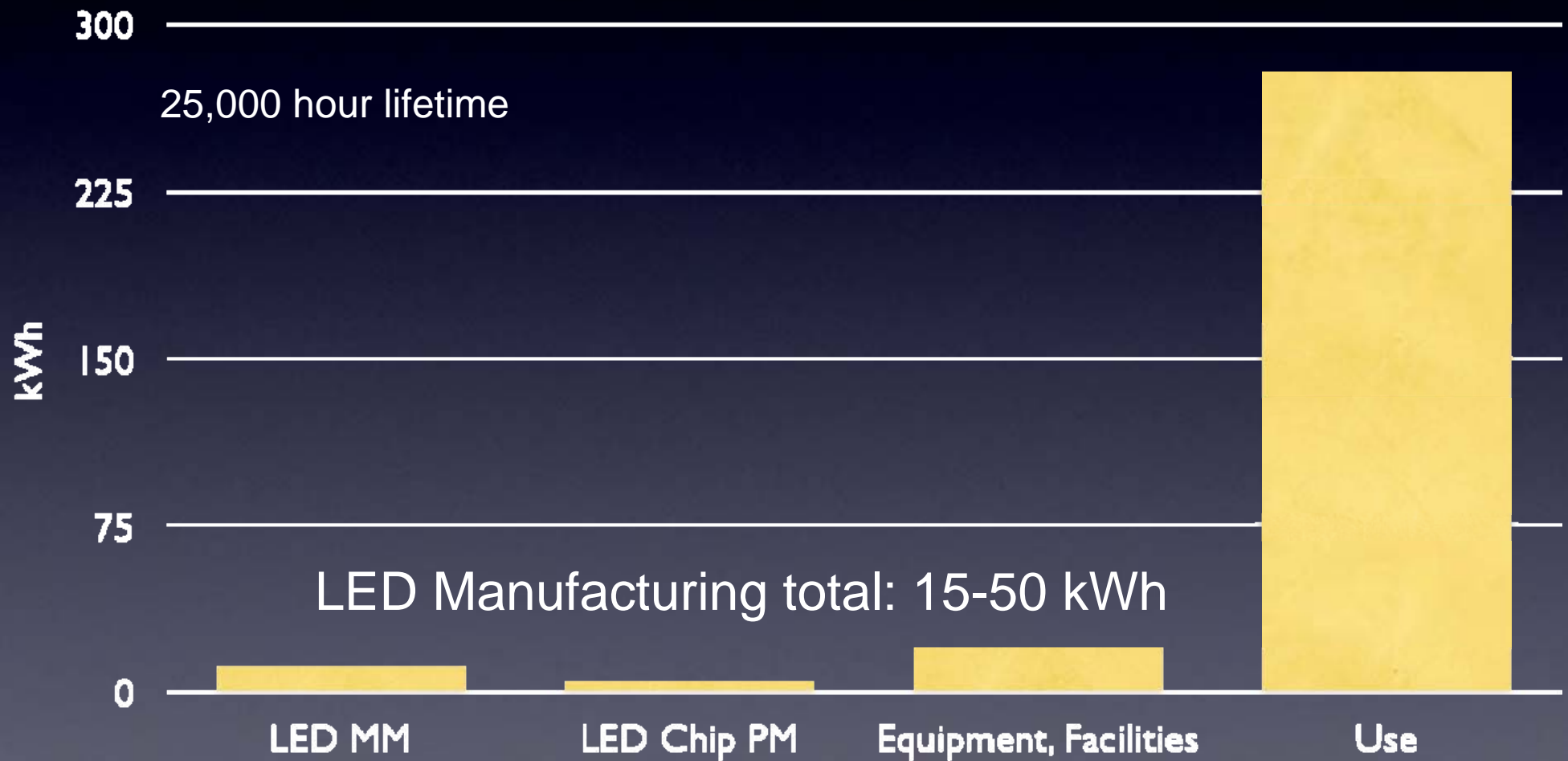
- Goal is to compare LEDs to current technologies in “functional equivalence”
- Current assumption: Functional unit = 25,000 hour lifetime of LED lamp in downlight setting
- Compare to best-in-class RCFL and incandescent using CALIPER data, correcting for output, efficacy, and lifetime

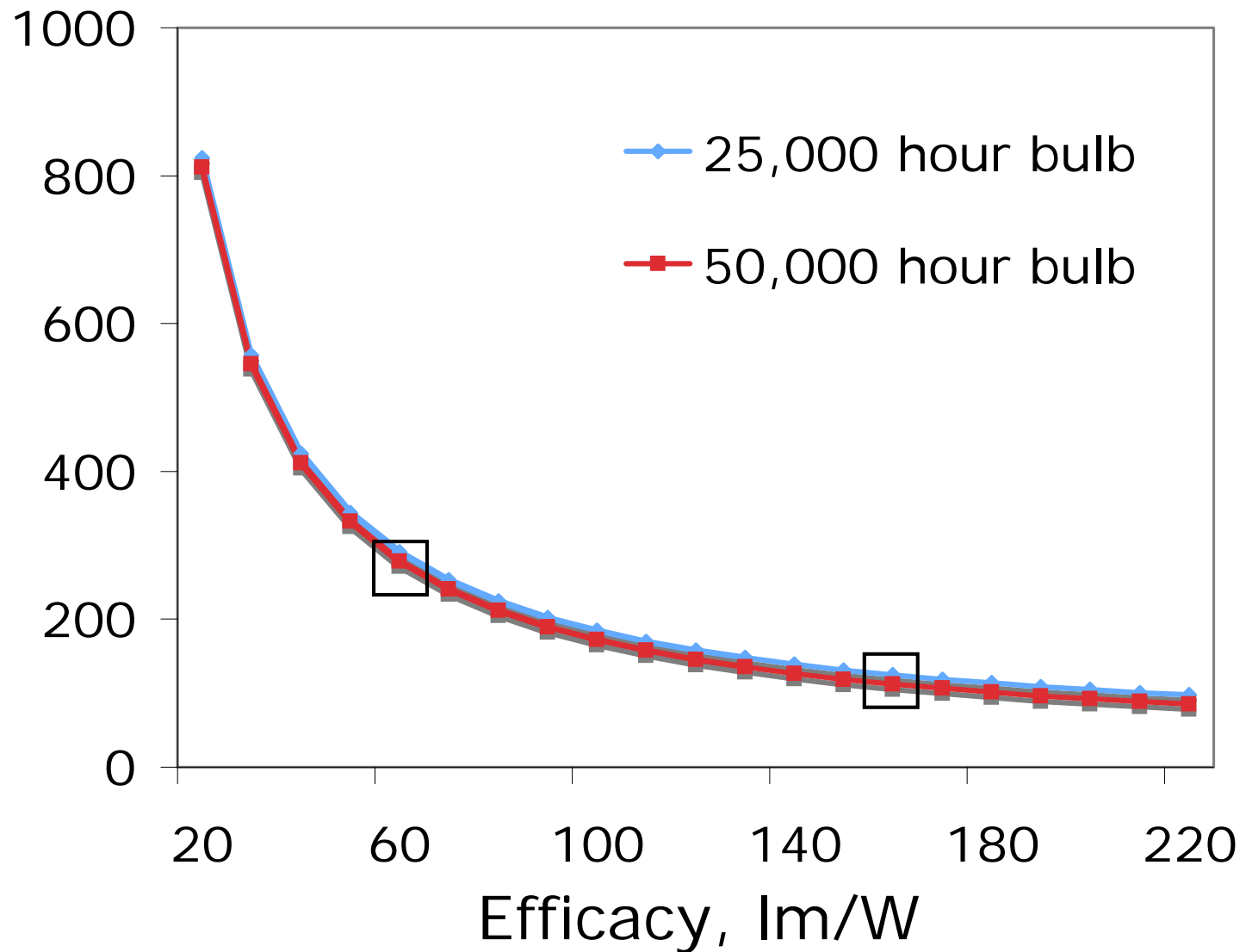
Use Phase

| | lm output | lm/W | lamps/f.u. | kWh/f.u. |
|-------------------------------|-----------|------|------------|----------|
| Incand R30 | 678 | 10.4 | 23.6 | 1500 |
| RCFL 15W | 653 | 50.2 | 3.1 | 320 |
| SSL Retrofit 25k life | 639 | 58.1 | 1.0 | 280 |
| SSL Retrofit 50k life | 639 | 58.1 | 0.5 | 280 |
| SSL Retrofit 50k life 2015 | 639 | 163 | 0.5 | 98 |

Source: 2005 Benchmark Summary CALIPER Report

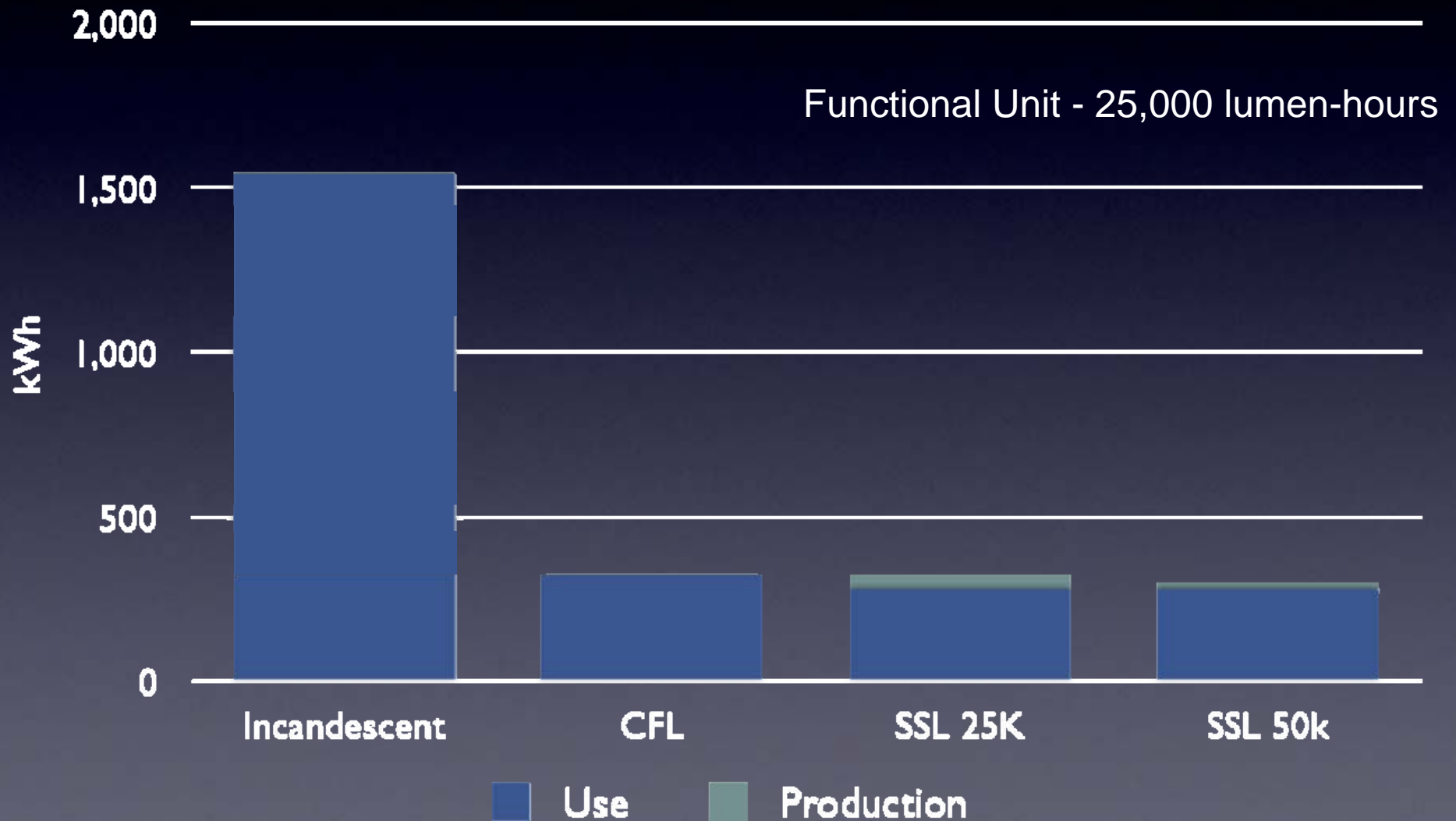
Preliminary LC Energy of SSL Product



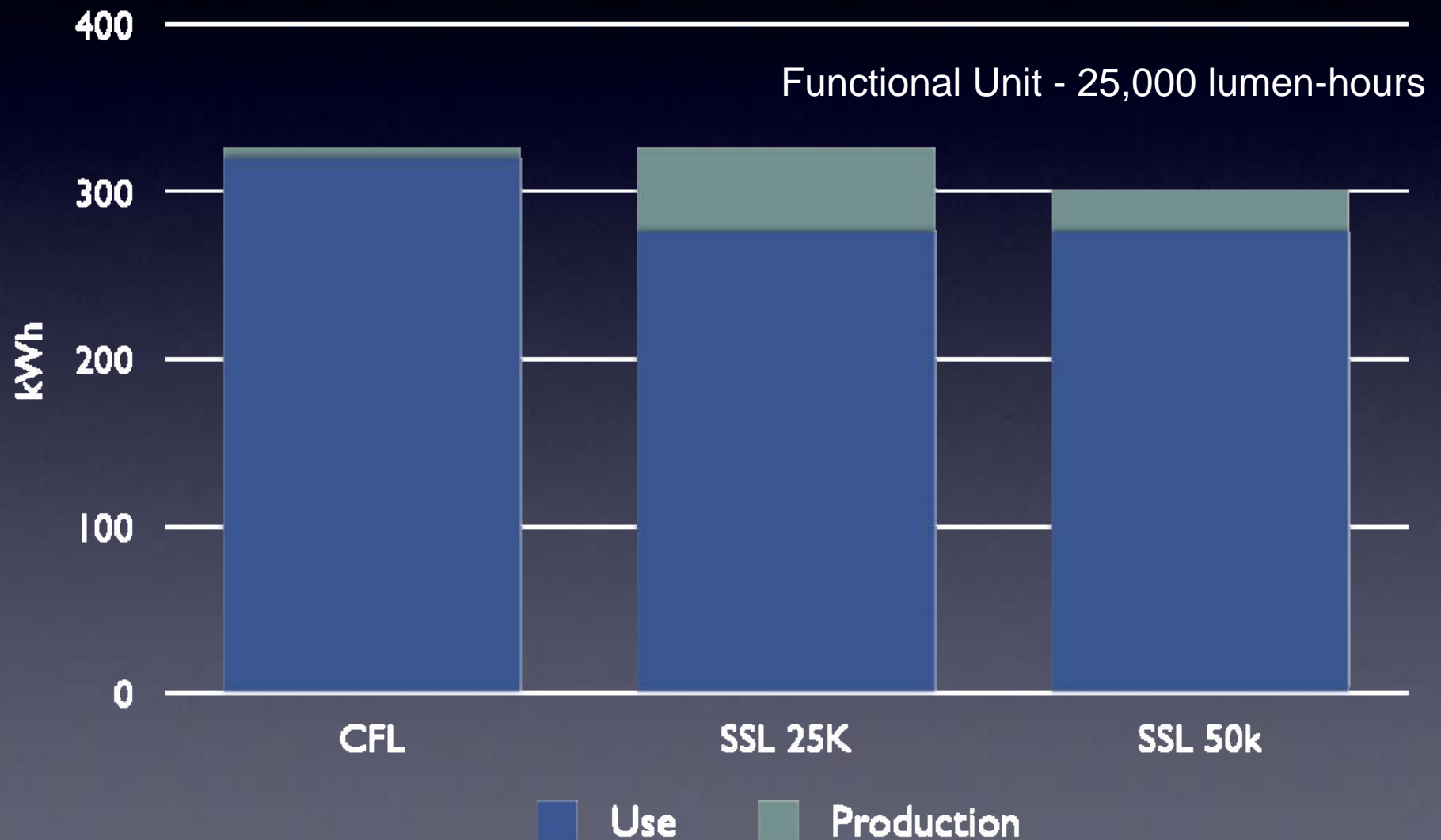


For the same lumen-hours of light,
bulb life is less important than efficacy

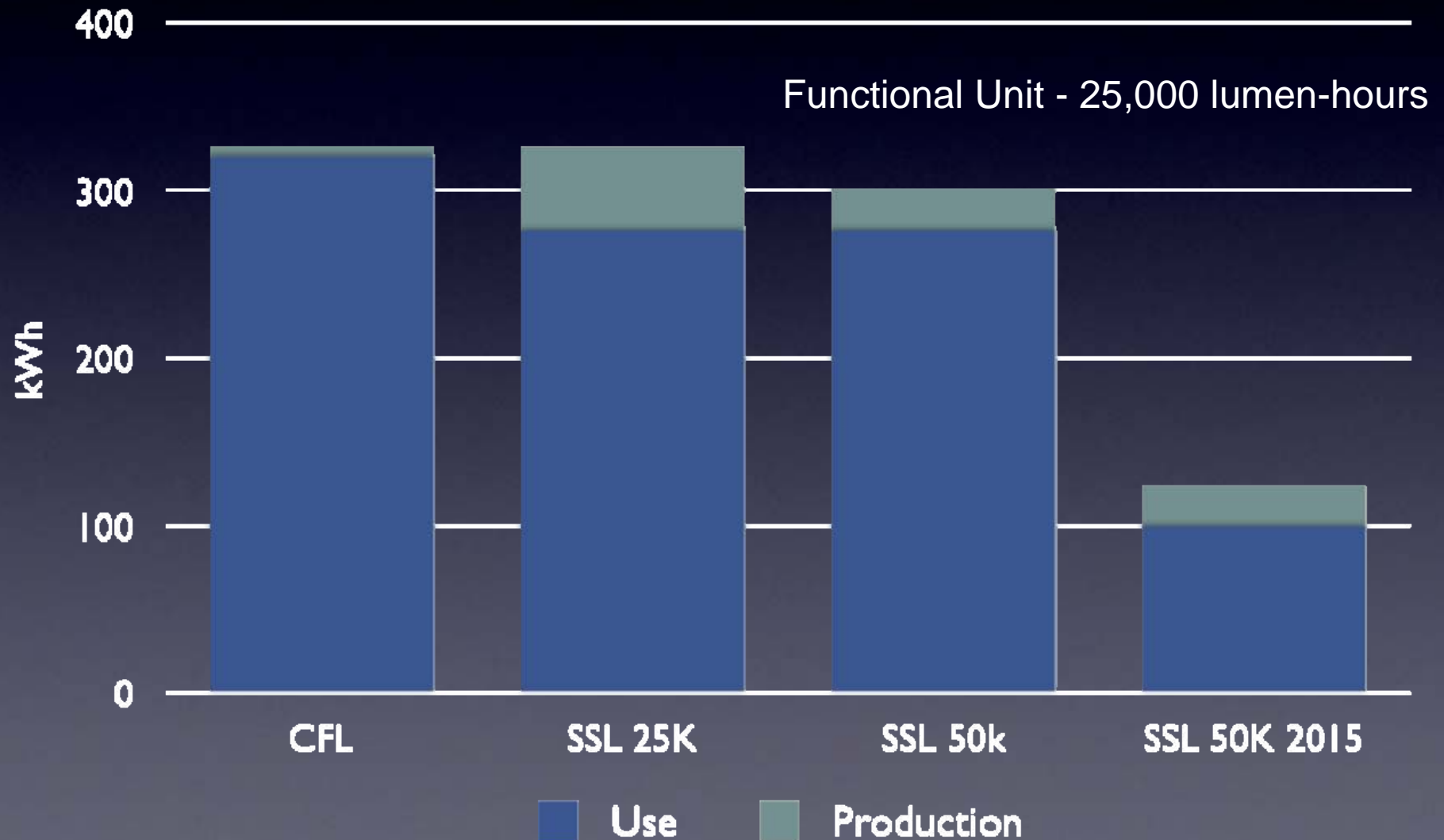
Life Cycle Energy Comparison of Lighting Technologies



Life Cycle Energy Comparison of Lighting Technologies



Life Cycle Energy Comparison of Lighting Technologies



Next steps

- Improve on preliminary data as presented here
- Expand boundary and acquire data for luminaire production, SSL end-of-life
- Consider other SSL products (e.g., retrofit luminaire not an Edison replacement)
- Begin materials inventory

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